LOW GENETIC DIVERSITY AND POOR DISPERSAL, BUT NOT CONSERVATION STATUS RANK, ARE LINKED TO CLIMATE CHANGE VULNERABILITY

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ABSTRACT

Climate change vulnerability assessments for Pennsylvania were completed for 35 plant species using the Climate Change Vulnerability Index (CCVI v2.0) developed by NatureServe. The CCVI allows the user to examine the exposure and sensitivity of a species to a series of risk factors associated with climate change. This study, as well as studies from West Virginia (Byers & Norris 2011) and New York (Schlesinger et al. 2011), indicates that among the top five risk factors, based upon both floral and fauna assessments, appeared to be related to a lack of dispersal and movement mechanisms along with low genetic diversity. All of the above studies found that conservation status rankings and vulnerability to climate change were not directly related to one another. In light of these findings conservation protocols need to be reexamined to direct resources where they will be most effective in furthering the conservation of plant species.

RESUMEN

Se completaron evaluaciones de vulnerabilidad por el cambio climático en Pennsylvania para 35 especies vegetales usando el Climate Change Vulnerability Index (CCVI v2.0) desarrollado por NatureServe. El CCVI permite al usuario examinar la exposición y sensibilidad de una especie a una serie de factores de riesgo asociados con el cambio climático. Este estudio, así como estudios de West Virginia (Byers & Norris 2011) y Nueva York (Schlesinger et al. 2011), indica que entre los cinco mayores factores de riesgo, basados en evaluaciones de flora y fauna, parecieron estar relacionados con una falta de mecanismos de dispersión y movimiento junto con una diversidad genética baja. Todos los estudios encontraron que las graduaciones de estatus de conservación y vulnerabilidad al cambio climático no estaban relacionadas directamente una con otra. A la luz de estos hallazgos los protocolos de conservación necesitan ser reexaminados para dirigir los recursos allí done son más efectivos el fomento de la conservación de especies vegetales.

INTRODUCTION

Global climate change (e.g., increasing temperatures, increased carbon dioxide levels, and altered patterns of precipitation) may alter the distribution of plant species and natural plant communities and may decrease habitat value for wildlife over broad segments of North America. A number of studies have shown that as climates warm, many species will suffer a decline in population and reduced range sizes while others will experience an increase in populations and range sizes. The relative vulnerability of species or habitats to climate change can be used to set goals, determine management priorities, and direct resources where they will be most effective in furthering the conservation of plant species biodiversity (Glick et al. 2011).

Climate change is only one of many stresses, or pressures from the external environment that plant species and their habitats are currently experiencing. The management strategies traditionally used to address conventional threats to biodiversity will likely be similar to those needed for threats induced by climate change. The list of plant taxa which are currently deemed most at risk will change as climate change alters species distribution and population viability, and re-emphasized strategies may become more important as habitats change.

One planning tool that is increasingly employed for conservation and management decisions is the vulnerability assessment. These assessments typically are models in which the inputs are characteristics of the species or ecosystems and the output is a rating of relative vulnerability. This type of risk assessment has historically been used in wildlife management and conservation programs but only recently has been available for addressing the threat of climate change (Boyce 1992; Ruggiero et al. 1994; Faith & Walker 1996). Vulnerabil-

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ity assessment can be especially useful to highlight new conservation targets and can be a useful way for states to address climate change in their state-wide conservation plans or to coordinate broad-scale policy efforts that span multiple agencies or political boundaries.

Several states such as New York (Schlesinger et al. 2011), Pennsylvania (Furedi et al. 2011), West Virginia, Nevada, Illinois, and Florida (https://connect.natureserve.org /science/climate-change/ccvi) have implemented NatureServe's Climate Change Vulnerability Index (CCVI; Young et al. 2010). One of the chief strengths of the CCVI is that it is designed to be used in conjunction with NatureServe's conservation status ranks (S-ranks; Master et al. 2009), which are an existing global standard for assessing conservation status based on rarity, trends, and threats. Another important strength lies in its explicit incorporation of scientific uncertainty into the assessment: assessors are free to pick a range of values for each factor, and this uncertainty is quantified in a Confidence score. Thus the CCVI considers how susceptible a species or a system is to climate change, while directly acknowledging inherent uncertainties in future conditions and species responses. Species in the northeast US are predicted to be exposed to increased temperatures and decreased moisture availability (ClimAid www.nyserda.ny.gov/climaid). However, each individual species is expected to vary in its sensitivity to these direct climate change impacts. Thus inherent species characteristics, such as dispersal ability, dependence upon or restriction to specific habitats, interspecific interactions, and genetic variation, will factor into the species' vulnerability to climate change.

NatureServe and various member programs, including the Pennsylvania Natural Heritage Program have assigned conservation status ranks to each species. These ranks provide an estimate of extinction risk for the plant species. The conservation status ranks, documented at the statewide geographic scale, are based on a one to five scale, ranging from critically imperiled (S1) to demonstrably secure (S5). The CCVI was designed to be used in conjunction with S-ranks; integrating climate change vulnerability assessments into existing lists of at-risk species can be considered a more holistic approach to conservation concerns. This study objective was to examine 35 plants of S1 and S2 ranking to see if there was a relationship between conservation status ranks and the CCVI index and then use a regression analysis to find the consistent risk factors across all taxonomic groups examined.

METHODS

Development of a priority assessment list

Rhoads and Klein (1993) reported 3318 taxa of vascular plants for Pennsylvania, which included 2076 native and 1242 introduced species. It was therefore necessary to develop a more refined list of priority species for the climate change vulnerability assessment. Previous reports conducted by Byers and Norris (2011), Furedi et al. (2011), and Schlesinger et al. (2011) used existing lists of species of conservation concern. Understanding the need for future monitoring of imperiled plant species in danger of extirpation due to climate change, we selected plant species with a NatureServe conservation status ranking of S1 (Critically Imperiled) and S2 (Imperiled) that occur or have been known to occur near one central site in the state. We did not consider habitat preferences, life forms, tolerance of disturbance, or species distribution patterns within the state of Pennsylvania. Following the criteria of imperiled conservation status and proximity to one central site, our set of plant taxa could be efficiently monitored in the future for range expansion, range contraction, extinction or maintenance, possibly due to climate change. The funding for this project limited our scope to 35 species.

Plant taxa of S1 and S2 ranking that have been known to occur within a 10-mile radius of Bedford, Pennsylvania, based upon herbarium label data of specimens from the Carnegie Museum of Natural History, were chosen for assessment. The city of Bedford is located in Bedford County in the south-central portion of the state within the Appalachian Mountain section of the Ridge and Valley Physiographic Province. A series of ridges, namely, Buffalo, Evitts, Tussey, and Polish Mountains and Warrior Ridge, run the length of this 10-mile radius from southwest to northeast. The Raystown Branch of the Juniata River flows through the circle west to east and its tributaries generally run in a northeasterly and southeasterly direction. Elevations in the 10-mile radius range from 2000 to 2500 feet along the ridges to 900 to 1200 feet along the valley floors. At a larger scale, these physical features of ridgelines and stream valleys are prominent and extensive features that provide continuous habitat over many miles. Variations in aspect, slope, and elevation of the ridge and valley province combine to create different habitats and microenvironments (Wagner 1998).

This 10-mile radius was also selected so that efficient monitoring program within a small geographic area could be implemented at a future date. Changes in distribution of species and plant communities potentially due to climate change may be most evident in populations of species occurring at various elevations and in a variety of habitats from ridgetop to steep slope and to wetland and floodplain areas along streams. For many imperiled species with relatively few populations overall, or occurring at the edge of their range, climate change may lead either to their extirpation or expansion in Pennsylvania.

Thirty-five plant species met the above criteria of conservation status and location. The list includes 17 perennial herbs, 1 biennial, and 2 annual herbs, 2 perennial vines, 5 shrubs, 1 subshrub, and 7 graminoids (full list of taxa at https://connect.natureserve.org sites/default/files/documents/Pennsylvania-Plant-CCVI-2012.pdf). Seven species are typically found in wetlands and eight species are typically deemed calciphiles with the remaining taxa occurring in mixed habitats. Two are known to be parasites and at least five are known to depend upon a mycorrhizal relationship. The NatureServe Climate Change Vulnerability Index (CCVI) Release 2.0 was applied to each of the 35 plant species.

Examination of species vulnerability to climate change

We scored each of the criteria (described below) using information from peer-reviewed published papers and reputable websites. Some criteria were more easily scored than others simply because of available information and previous research. Accurate information on effective pollinators is nonexistent, or untested, for many of the plant species, and dispersal mechanisms are more often hypothesized than experimentally proven. Fortunately the index is designed so that the accumulated knowledge of the plant species or genera allows for choosing a range of values.

Vulnerability to climate change was assessed by considering the two main components of vulnerability as defined by Williams et al. (2008): the exposure of a species to climate change within a defined area combined with the sensitivity of a species to climate change. Vulnerability assessment involves describing the severity and scope of the exposure that species experience, and combining this with species' sensitivity and capacity to adapt to climate change. NatureServe's newly developed Climate Change Vulnerability Index (Young et al. 2010) provides a means of dividing species into groupings of relative risk to climate change and of identifying key factors causing species to be vulnerable. Used with standard conservation status assessments such as the NatureServe G- and S-rank system, the Index can help land managers evaluate the likely effectiveness of alternative strategies to promote adaptation of species to climate change as well as select key species to monitor. It is designed to complement, and not duplicate, information contained in the NatureServe conservation status ranks (Master et al. 2009), and may be used to update conservation status ranks to include the additional stressor of climate change. Using regionally specific climate models, the index examines how the changed climate will impact a species using factors known to be associated with vulnerability to climate change, including species-specific factors as well as external stressors imposed by human actions. Downscaled climate data representing an ensemble of 16 global circulation models were downloaded from Climate Wizard (Girvetz et al. 2009) and displayed in a GIS format. Climate data were available on a 4-km grid for historical data, and a 12-km grid for predicted future data. The overlap of changing climate with each species' range was used to calculate direct exposure.

The factors considered in evaluating species response might be divided into general categories including direct exposure, indirect exposure, sensitivity, documented response, and modeled response. Detailed information including the scientific references used to develop each factor and the limitations of the methodology are given in Young et al. (2010).

Brief definitions of the factors are given below and scored NatureServe's Climate Change Vulnerability Index Table (https://connect.natureserve.org/science/climate-change/ccvi).

A—Direct Exposure
Temperature change is the predicted change in annual temperature by 2050, calculated over the range of the species in Pennsylvania (ClimateWizard).

Moisture change is the predicted net change in moisture based on the Hamon AET:PET moisture Metric by 2050, calculated over the range of the species in Pennsylvania (Kartesz 2011; WCRP, Maurer et al. 2007; ClimateWizard) (Figs. 1 & 2).

B—Indirect Exposure

B1: Exposure to Sea Level Rise
Weiss et al (2011) predict that only a very small portion of Pennsylvania will be subject to a sea level rise of 0.5 to 1 meter; accordingly, less than 10% of the range of plant species eligible for this study could be subject to sea level rise.

B2: Distribution relative to Barriers
Given the topography and geographical context of the state, most plant species in Pennsylvania will not be subject to natural or anthropogenic barriers such as high mountain ranges, large expanses of water, or intensive agricultural or urban development.

B3: Predicted impact of land-use changes resulting from human responses to climate change
Forestland in Pennsylvania totals 58% of land cover and is the dominant land class at 166 million acres. This proportion remained stable from 1989 to 2004; the state's forest loss (primarily due to residential and industrial development) was offset by conversion of agricultural land to forest through natural succession (Pennsylvania's Forest 2004). Nowak & Walton (2005) predicted that if growth trends of the 1990s continued through 2050, urban development could subsume an additional 15 million acres. Even if this loss cannot be offset by agricultural land conversion, forestland should still be a primary land class. Forest fragmentation and smaller patch sizes are prevalent in the southeast and west, but, in the north-central region, forest patches are large and contain more interior forest habitat (Pennsylvania's Forest 2004).

Twenty-nine percent of the forest land is owned by the state and federal US Forest Service. Government agencies are likely, as part of their management plans, to manage the forests for mitigation-related carbon storage and carbon sequestration. The majority of forest-land, 71%, is privately owned (Pennsylvania's Forest 2004).

C—Sensitivity

C-1: Dispersal—The ability of a species to shift locations in response to climate change (Vittoz & Engler 2007). For seed dispersal distances we used a typology based on dispersal modes and plant traits.

C-2: Predicted sensitivity to temperature and moisture changes: Species requiring specific precipitation and temperature regimes may be less likely to find similar areas as climates.

C-2-a: Predicted sensitivity to changes in temperatures.

C-2-b: Predicted sensitivity to changes in precipitation, hydrology, or moisture regime.

C-2-c: Dependence on a specific disturbance regime likely to be impacted by climate change. Species dependent on habitats such as prairies, or are maintained by regular disturbances such as fire or flooding are vulnerable to climate change.

C-2-d: Dependence on ice, ice-edge, or snow-cover habitats. This factor is of minor significance depending on a species' range in PA.

C-3: Physical Habitat Specificity. Species requiring specific soils (limestone outcrops) or physical features such as caves, cliffs or sand dunes may become vulnerable to climate change.

C-4: Reliance on Interspecific Interactions. Species with tight relationships with other species may be threatened by climate change.

C-4-a: Dependence on other species to generate habitat

C-4-c: Pollinator versatility

C-4-d: Dependence on other species for propagule dispersal

C-4-e: Forms part of an interspecific interaction not covered above

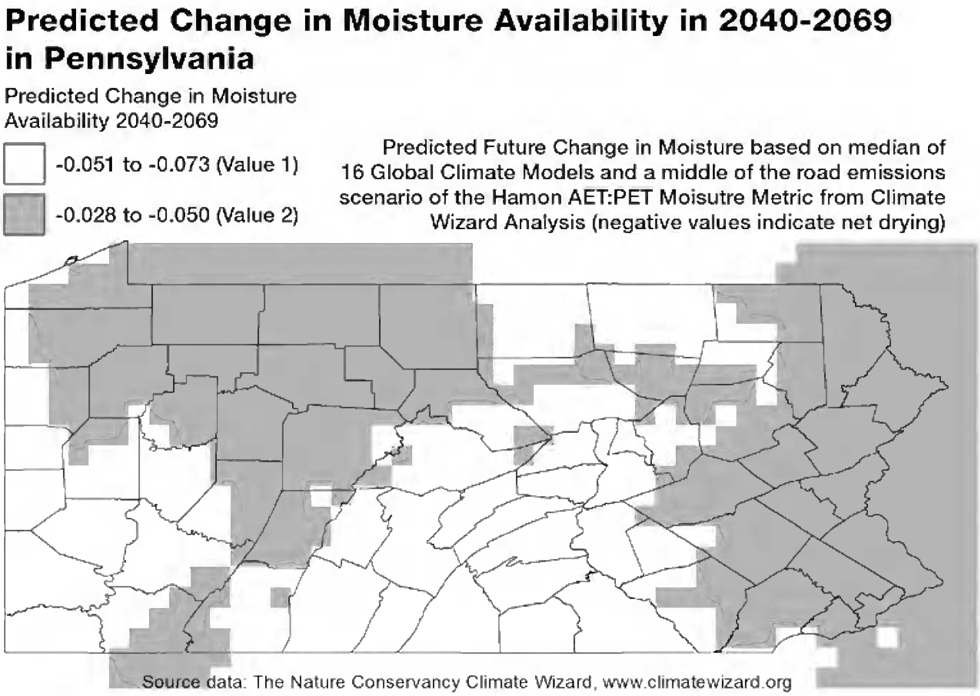

Fig. 1. Predicted future change in Pennsylvania moisture availability. Based on median of 16 global climate models and a middle-of-the-road emissions scenario of the Hamon AET:PET moisture metric from Climate Wizard Analysis. Negative values indicate net drying.]

C-5: Genetic Factors—A species' ability to evolve adaptations to environmental conditions brought about by climate change is largely dependent on its existing genetic variation.

We used the internal transcribed spacer (ITS) gene because it contained the most data at this generic level. The ITS region of nuclear ribosomal DNA (nrDNA) has proven to be a valuable resource for plant systematics as a useful source of characters for phylogenetic studies in many angiosperm families (Baldwin et al. 1995). We scored the number of parsimony informative characters, a common measure of genetic variation. If the number of parsimony informative characters was under 150 then we coded the factor as increasing vulnerability to climate change; between 151–250 was coded as somewhat increasing vulnerability; between 251–350 we coded as neutral and over 351 was coded as somewhat decreasing vulnerability.

C-6: Phenological response to changing seasonal temperature and precipitation regimes. Recent research suggests that some phylogenetic groups are declining due to lack of response to changing annual temperature dynamics (e.g., earlier spring, longer growing season), including some temperate zone plants that are not moving their flowering times.

D—Documented or Modeled Response to Climate Change

D-1: Documented responses to recent climate change: The results of published research may be available that document changes within species that can be definitively linked to climate change.

D-2: Modeled future change in range or population size: The change in area of the predicted future range relative to the current range is a useful indicator of vulnerability to climate change.

D-3: Overlap of modeled future range with current range: The results of future distribution models can be compared to current range maps to address potential overlap.

D-4: Occurrences of protected areas in modeled future distribution: The results of future distribution

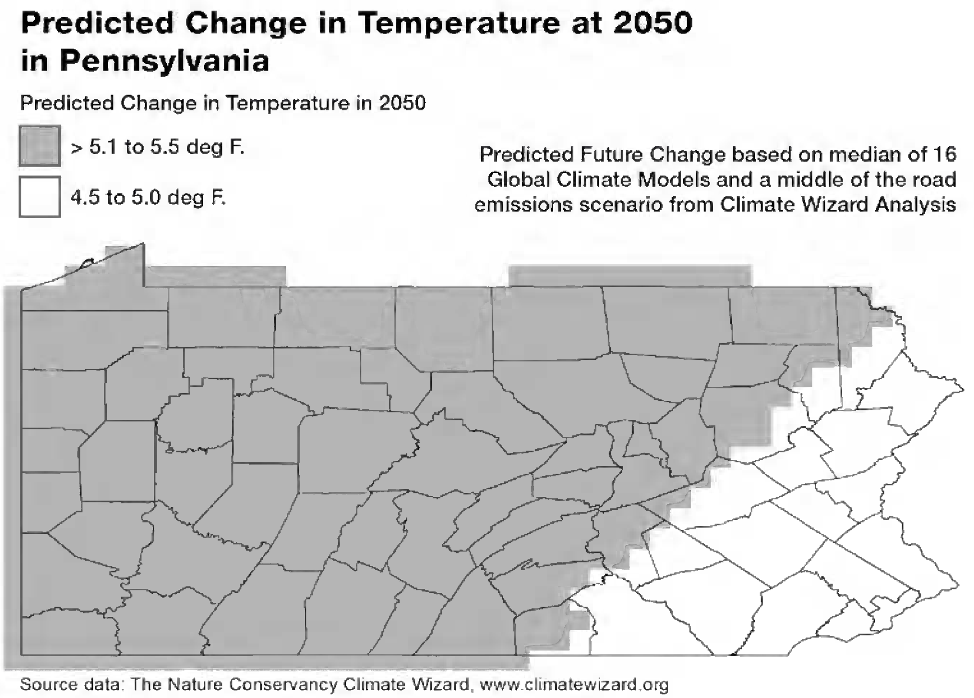

Fig. 2. Predicted future temperature change in Pennsylvania. Based on median of 16 global climate models and a middle-of-the-road emissions scenario from Climate Wizard Analysis.]

models can be compared to present protected areas to see if future ranges may fall entirely outside of protected areas and therefore compromise their long-term viability.

Compile and analyze results: Climate Change Vulnerability Index results were compiled and analyzed in order to (a) highlight those species most (and least) vulnerable to climate change, (b) identify and rank causative factors, and (c) identify geographic areas or habitat types at high risk.

Regression analysis

To determine the factors most important in assessing vulnerability, we followed the methodology used by Schlesinger et al. (2011). We built classification trees using the Random Forests (Breiman 2001; Liaw & Wiener 2002) package in R (R Development Core Team 2011), a technique from the field of machine learning. The Random Forests routine is to build thousands of classification and regression trees using bootstrap samples of the data set and predictors. We limited our predictor variables to the exposure and sensitivity variables influencing vulnerability (i.e., omitting documented and modeled responses) and imputed (estimated) values recorded as "Unknown," as the routine does not accept missing data.

RESULTS AND DISCUSSION

Documented responses to climate change are incorporated into NatureServes Climate Change Vulnerability Index Table. The output is one of five categories of vulnerability and one indicating lack of evidence. Definitions, and the abbreviations that are used throughout this document, follow Young et al. (2010) and are presented in Table 1.

Plant species assessed and factors affecting vulnerability

The 35 plants included in this assessment ranged from highly vulnerable to not vulnerable to climate change.

Table 1. Five Vulnerability Index scores and eight individual Risk Factor scores.

Vulnerability Index	
EV (Extremely Vulnerable)	Abundance and/or range extent within geographical area assessed extremely likely to substantially decrease or disappear by 2050; HV Highly Vulnerable Abundance and/or range extent within geographical area assessed likely to to decrease significantly by 2050.
MV (Moderately Vulnerable)	Abundance and/or range extent within geographical area assessed likely to decrease by 2050.
PS (Not Vulnerable/Presumed Stable)	Available evidence does not suggest that abundance and/or range extent within geographical area assessed will change (increase/decrease) substantially by 2050. Actual range boundaries may change.
IL (Not Vulnerable/Increase Likely)	Available evidence suggests that abundance and/or range extent within geographical area assessed is likely to increase by 2050.
Risk Factor:	
GI	Greatly Increase Vulnerability
Inc	Increase Vulnerability
SI	Somewhat Increase Vulnerability
N	Neutral
SD	Somewhat Decrease Vulnerability
D	Decrease Vulnerability
N/A	Not Applicable
U	Unknown

Vulnerability to climate change was due to a combination of multiple risk factors. Influential risk factors appear to be limited dispersal capabilities, decreased genetic variation, and dependence on a specific hydrological or moisture regime. Plants assessed as stable were often habitat generalists and less dependent upon a wetland habitat, were able to disperse longer distances, and were genetically more diverse. For example, *Astragalus canadensis*, a plant somewhat dependent upon marshy ground or moist prairie, rarely disperses more than 10 meters when its exploding fruit ejects its seeds (Gleason & Cronquist 1991). ITS phylogenetic inference revealed a low number of parsimony information characters and thus low genetic variation. Its vulnerability index score was Moderately Vulnerable. On the other hand, *Amelanchier sanguinea*, a shrub found in an assortment of habitats throughout its range, produces sweet and juicy fruits highly palatable to birds (Gleason & Cronquist 1991 and PNHP Factsheet). ITS phylogenetic inference revealed a higher number of parsimony information characters and thus higher genetic variation. Its vulnerability index score was Not Vulnerable.

Fourteen of the 35 (40%) species assessed were determined to be vulnerable (HV or MV) to climate change. None of the species were rated as "Extremely Vulnerable" and only two as "Highly Vulnerable." Twenty species (57%) were rated as "Presumed Stable" and only one as "Increase Likely." Both of the "Highly Vulnerable" species are poor dispersers.

All 35 species assessed were ranked S1, S1S2, or S2. The vulnerability statuses were distributed throughout these conservation status ranks. Fifteen of the 35 species examined were S1 ranked (imperiled species), 8 of these taxa were presumed stable. S1 species did not appear to be more vulnerable to climate change than did the S2 species (Fig. 3).

A review of global conservations ranks found only four taxa were at some risk to global extinction. These were ranked G2 (globally imperiled – at high risk of extinction due to very restricted range, few populations, etc.) or G3 (vulnerable – at moderate risk of extinction due to restricted range, relatively few populations, etc.). Their vulnerability status was Presumed Stable. The remaining 31 species were ranked G4 (apparently secure) or G5 (secure), and the vulnerability statuses included Increase Likely, Presumed Stable, Moderately and Highly Vulnerable (Fig. 4).

An important result of this assessment is that we cannot predict the climate change vulnerability of a species based on its current Conservation Status Rank (G=global or S=state rank). Rare species may not always be vulnerable to climate change and common species are not necessarily resilient. Each species will behave and respond according to its unique life history characteristics, habitat requirements, and distribution. The impli-

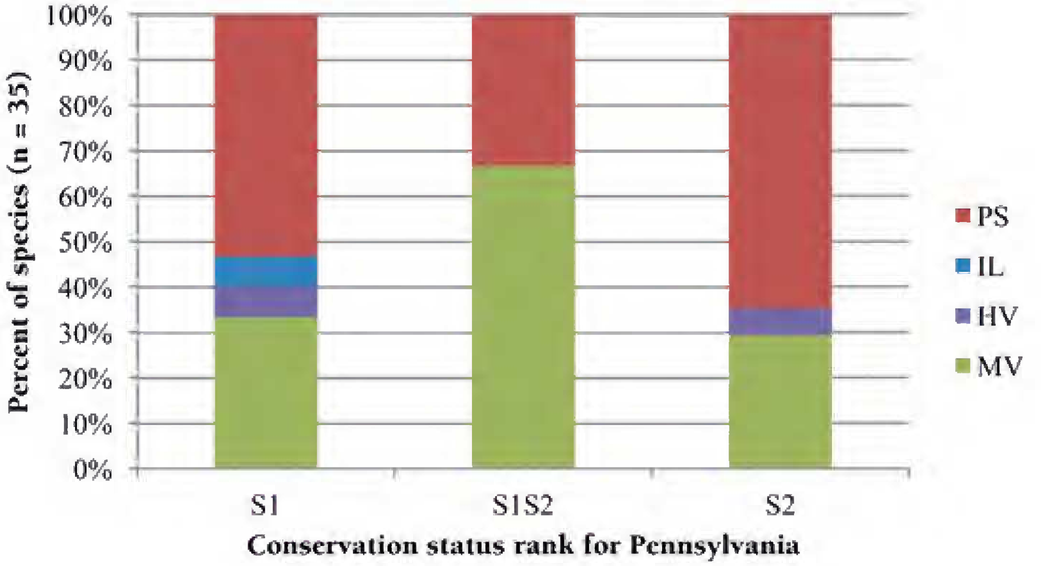

Fig. 3. Percent of species within state conservation status ranks in each vulnerability category (S1 n=15, S1S2 n=3 and S2 n=17). **PS**= Presumed Stable; **IL**= Increase Likely; **HV**= Highly Vulnerable; **MV**= Moderately Vulnerable. Adapted from Byers and Norris (2011) and Schlesinger et al. (2011).

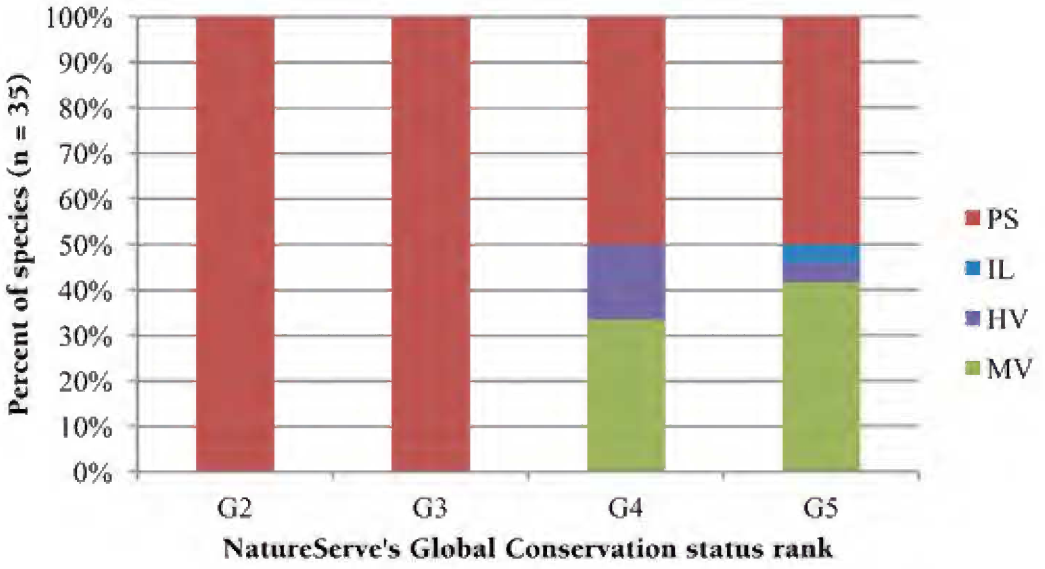

Fig. 4. Percent of species within global conservation status ranks in each vulnerability category (G2 n=2; G3 n=2; G4 n=25; and G5 n=6). **PS**= Presumed Stable; **IL**= Increase Likely; **HV**= Highly Vulnerable; **MV**= Moderately Vulnerable. Adapted from Byers and Norris (2011) and Schlesinger et al. (2011).

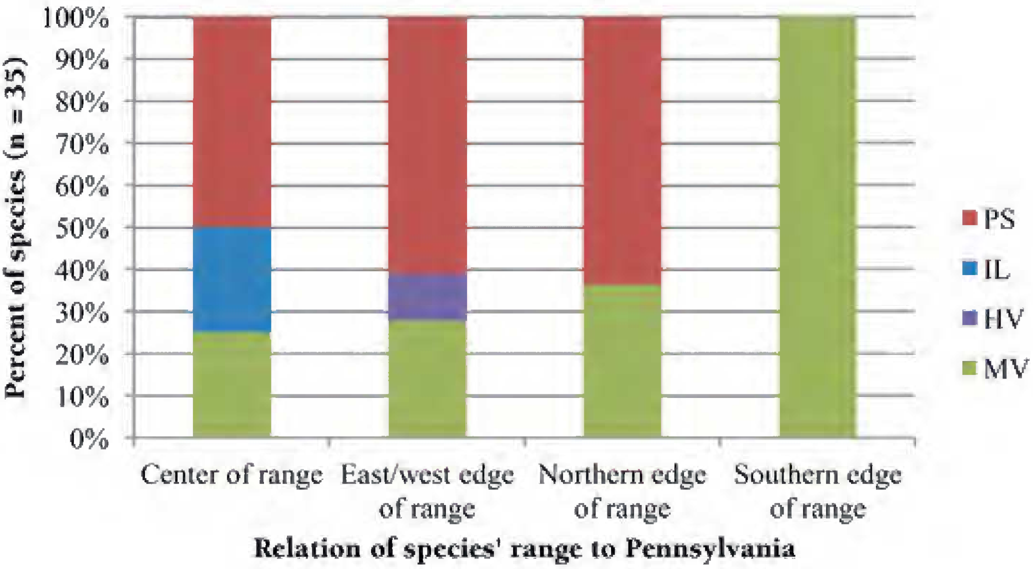

Fig. 5. Percent of species in each vulnerability category categorized according to the position of their range relative to Pennsylvania (Center n=4; East/West n=18; North n=11; and Southern n=2). PS= Presumed Stable; IL= Increase Likely; HV= Highly Vulnerable; MV= Moderately Vulnerable. Adapted from Byers and Norris (2011) and Schlesinger et al. (2011).

cations of this are important to rare plant conservation and management strategies, since climate change may necessitate the reassessment of conservation status. We need to examine and re-align our ranking process to best conserve species and habitats with the resources available.

Both species at the southern edge of their range were assessed as Moderately Vulnerable, and therefore possibly disappearing from the state (Fig. 5), whereas the Center of the range, East/West edge of the range and Northern edge of the range contained 50% or greater of the Presumed Stable (PS) taxa and were assessed as not highly vulnerable to climate change.

Dispersal scores ranged from somewhat decrease vulnerability to greatly increase vulnerability (Fig. 6) and did have an influence. Twelve of the 25 species were scored as GI, Inc, and SI indicating dispersal limitations and were assessed as Highly Vulnerable (HV) or Moderately Vulnerable (MV). The taxa with overall neutral and somewhat decreased vulnerable scores consisted of mostly Presumed Stable (PS) taxa (7 of the 10 species) indicating no dispersal or movement influence. These results also agree with the first Pennsylvania study (Furedi et al. 2011), West Virginia (Byers & Norris 2011) and New York (Schlesinger et al. 2011) climate change vulnerability assessment reports. These reports indicated that the top risk factors, based upon both floral and fauna assessments, appeared to be related to dispersal and movement mechanisms. Plants that lack the specialized structures for dispersal by wind, or lack attractive coloration for animal dispersal, have limited potential for long-distance dispersal.

Measured genetic variation scores were an influence (Fig. 7). Nine of the seventeen species in the Inc and SI categories indicated low genetic diversity, assessed as Highly Vulnerable (HV) or Moderately Vulnerable (MV). Taxa with the overall neutral and somewhat decreased vulnerable scores consisted of mostly Presumed Stable (PS) taxa (11 out of 16 species) and were assessed as not vulnerable to climate change. This study used the number of parsimony informative characters of the ITS gene as an indicator of genetic diversity. ITS (internal transcribed spacer) region was selected because it is typically used at the species level. Although additional assessment needs to be done using this technique, it was in agreement with other factors used in this study and

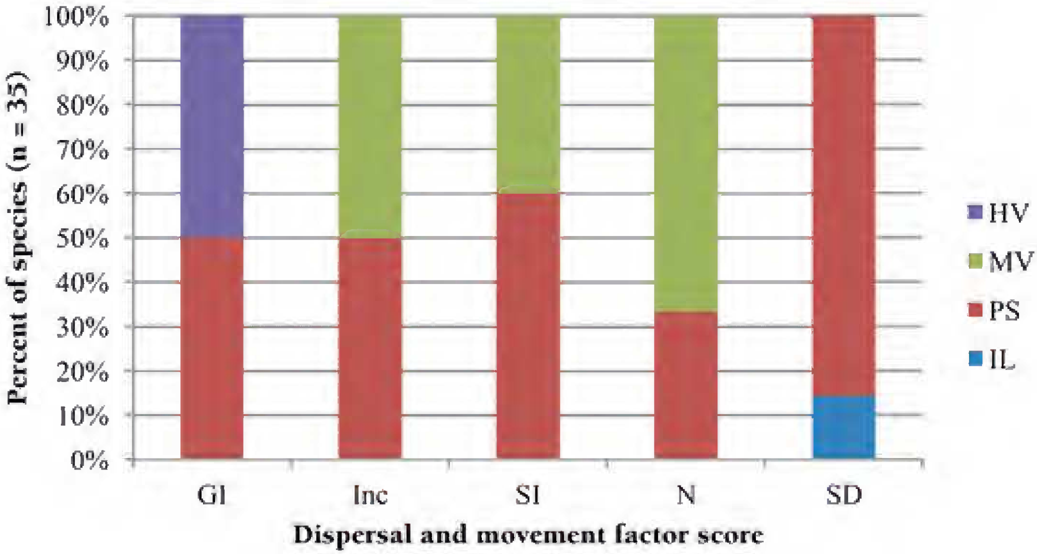

Fig. 6. Percent of species in each vulnerability category categorized according to the dispersal and movement factor relative to Pennsylvania (GI=Greatly Increase Vulnerability n=4; Inc=Increase Vulnerability, n=16; SI=Somewhat Increase Vulnerability, n=5; N=Neutral, n= 3; and SD=Somewhat Decrease Vulnerability, n=7). **PS**= Presumed Stable; **IL**= Increase Likely; **HV**= Highly Vulnerable; **MV**= Moderately Vulnerable. Adapted from Byers and Norris (2011) and Schlesinger et al. (2011).

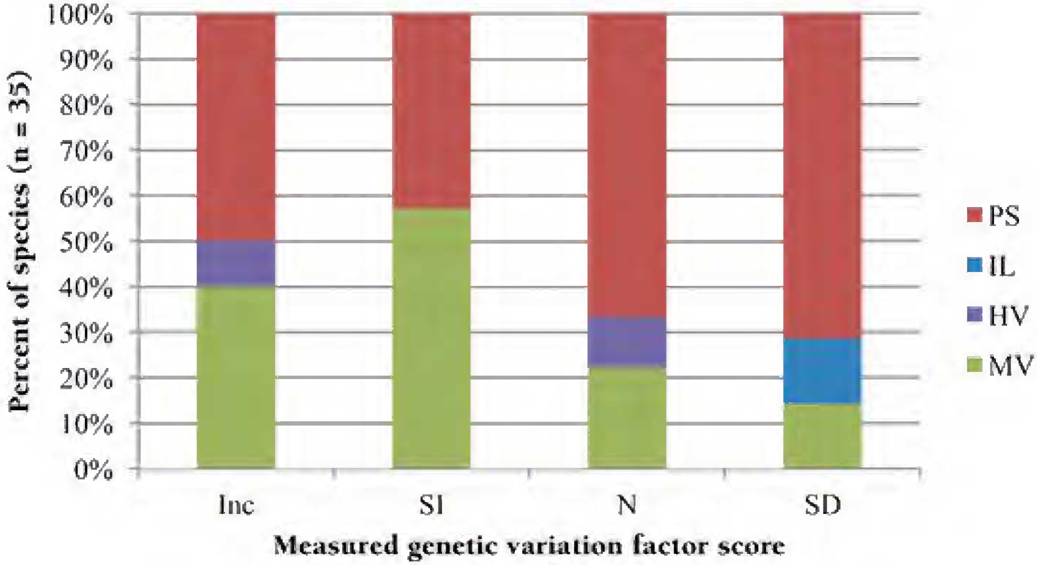

Fig. 7. Percent of species in each vulnerability category categorized according to the measured genetic variation factor relative to Pennsylvania (Inc=Increase, n=10; SI=Somewhat Increase Vulnerability, n=7; N=Neutral, n= 9; SD=Somewhat Decease Vulnerability, n=7; and U=Unknown, n=2). **PS**= Presumed Stable; **IL**= Increase Likely; **HV**= Highly Vulnerable; **MV**= Moderately Vulnerable. Adapted from Byers and Norris (2011) and Schlesinger et al. (2011).

with the results from West Virginia and New York. The previous Pennsylvania study did not contain enough genetic data to be significant. As stated, these results also agree with the West Virginia (Byers & Norris 2011) and the New York (Schlesinger et al. 2011) state climate change vulnerability assessment reports. Both of these reports indicated that genetic factors predisposing species to potential climate change effects were easily the most important factor. Species with reduced genetic variation are less likely to be able to respond to environmental change (e.g., Aitken et al. 2008). In addition, plants with poor dispersal strategies will eventually be genetically bottlenecked and therefore have low genetic diversity (http://www.nature.com/scitable/definition/population-bottleneck-300).

Regression scores

The most important factors, as indicated by the R^2 values, driving a species' vulnerability status were as follows:

1. Dispersal and movement;
2. Predicted sensitivity to changes in precipitation, hydrology, or moisture regime;
3. Predicted sensitivity to changes in temperature;
4. Physiological hydrological niche (a dependence on a narrow precipitation/hydrologic regime), and
5. Genetic factors.

These top five factors are probably representative of the most consistent risk factors across all plant taxonomic groups in the state.

The random forest regression analysis supports the visual assessments of the graphs. Dispersal limitations, the ability of a species to shift locations in response to climate change, were one of the most important factors in our assessment. The next most important factors were temperature and moisture. Those species requiring moist microhabitats will experience stress if these habitats dry up. Finally genetic variation, which affects a species' ability to adapt to environmental conditions, was among the top five factors (Fig. 8).

Comparisons to other states

Three states in the Northeast—Pennsylvania, New York and West Virginia—have recently completed CCVI analyses, but only Pennsylvania and West Virginia included plants. Our study contained 2 out of 35 taxa as highly vulnerable whereas the first Pennsylvania analysis contained 24 out of 40 taxa as extremely (EV) to highly vulnerable (HV) and West Virginia contained 7 out of 33 plant taxa as (EV or HV). The proportion of species assessed as vulnerable depends greatly on the species selected for analysis, as conducting the analysis on all species is not possible given constraints of funding, time and available information. Other studies aimed to select species they thought might prove vulnerable to climate change based on habitat; however, we selected taxa based on their current Conservation Status State Rank (imperiled or endangered species).

Our results agreed with those of West Virginia while there was no overlap between our study and the first Pennsylvania analysis. Our study and the West Virginia study assessed 2 species in common. The final index values either matched exactly (*Pycnanthemeum torreyi*) or were off by one step (*Paxistima canbyi*, Presumed Stable versus Moderately Vulnerable). These differences in index values might result from true differences in vulnerability among states or differences in interpretation of data; a full analysis of these differences is beyond the scope of this study.

Management and monitoring recommendation

A complete discussion of management, monitoring and restoration of habitat connectivity is past the capacity of this paper. However, we can provide some recommendations that are applicable here based on our results.

The fact that the species assessed as Highly Vulnerable in our analyses are associated with the identification of barriers to dispersal as an important component of our vulnerability and regression scores. Maintaining and restoring habitat connectivity is crucial for many ecological processes, including dispersal, gene flow, and movement in response to climate change (Mawdsley et al. 2009; Heller & Zavaleta 2009; Byers & Norris 2011; McRae et al. 2012). This is especially true for vulnerable species restricted to certain habitats. Another valuable outcome of this procedure is it allows biologists to ascertain which life history traits of a particular species in-

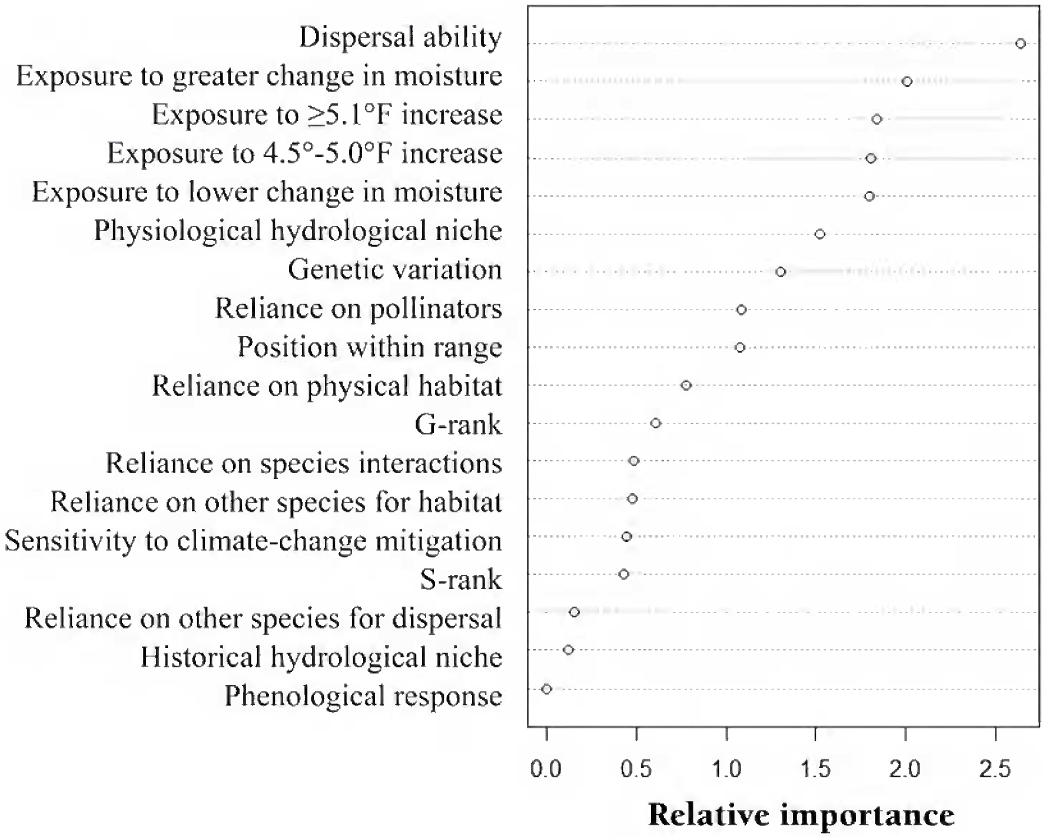

Fig. 8. Variable importance (decrease in node impurity according to the Gini index) from the random forest analysis of Climate Change Vulnerability Index scores of 35 Pennsylvania plants.

dicate propensity of that species to be vulnerable to climate change and further highlights other factors that might pose more immediate threats to certain imperiled species (such as dispersal limitations and low genetic diversity). Species with good dispersal mechanisms can redistribute themselves, but the key to successful movement and migration is the presence of contiguous habitats that species are able to colonize or move across. Protecting large blocks of unfragmented habitats and using linkages and corridors to enhance connectivity will facilitate this colonization or movement, but this is only one solution. Developing methods to identify barriers whose removal would significantly improve connectivity, such as least-cost and simulation modeling, can be cost effective and broaden alternatives available to connectivity conservation. This network of intact habitats should represent a full range of ecosystems to sustain biodiversity and genetic diversity. Key ecological processes such as pollination, seed dispersal, nutrient cycling, and natural disturbance cycles will be maintained under this environment.

Long-term monitoring using multiple taxa and habitats will help 1) test hypotheses about vulnerability; 2) detect changes in species; 3) test hypotheses about consistent risk factors; 4) identify barriers to improve connectivity; and 5) help examine alternative methods for least-cost simulation modeling to maintain connectivity. Currently, these data are not readily available and it is imperative for governmental and non-governmental organization to have these data to make the most informed conservation and management decisions. The success in combating these environment changes will only be achievable through an unprecedented level of collaboration and cooperation between wildlife managers, other organizations, scientists, and the public. Building science-driven strategies that maximize the use of scarce resources will be necessary so legislative support and policy changes can be implemented. In order to facilitate long-term monitoring of multiple taxa we have used herbarium data to designate a 10-mile radius in Bedford County including most of the plants we analyzed in this study. Additional sites could be established using the same techniques (i.e. a small number of species within a defined radius), so a manageable monitoring program could be funded in the future allowing for improved collaboration and cooperation between organizations which reduce the cost of research yet obtain a wealth of information so good conservation decisions are made.

Proposed taxa for more detailed monitoring programs

Broad-scale, long-term monitoring of taxa will help test hypotheses about vulnerability, which are essentially what the CCVI provides. Monitoring can detect unanticipated changes in populations, can identify particular stressors, and can reveal range shifts and changes in phenology. Long-term monitoring has already revealed shifts that have been vital in demonstrating responses to climate change (Parmesan et al. 1999; Hitch & Leberg 2007; Zuckerberg et al. 2010). There is a pressing need to establish a solid baseline of data that will allow us to detect these changes in Pennsylvania and make the most informed conservation and management decisions. As new factors affect wildlife and habitats, such as changes in phenology and the effects on pollinators and the increase in invasive species, managers will need to monitor these changes and incorporate them into new action strategies.

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